ASD TECHNICAL NOTE 61-35

The Influence of Supersonic Airflow on Aerial Photography

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AERONAUTICAL SYSTEMS DIVISION

NOTICES

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Aeronautical Systems Division
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United States Air Force
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FOREWORD

This technical note was prepared by the Recon Data Reduction Branch, Reconnaissance Laboratory, Avionics Division, Directorate of Advanced Systems Technology, Aeronautical System Division. The experimental work was performed by the group now designated ASRNRD-4 during 1957 as an in-house effort under Task 62794 of Project 6220.

Mr. Hermann R. Mestwerdt served as task engineer and Dr. Werner Rambauske of the University of Dayton served as technical consultant.

The authors gratefully acknowledge the technical advice and support in the aerodynamic aspects given by Mr. W. P. Zima and Captain Strong of the Wind Tunnel Branch of the Aircraft Laboratory.

This technical note combines two informal reports that were written in January and October 1957 by the same authors.

ABSTRACT

The influence of a turbulent boundary layer, as it affects refraction, dispersion, and scattering of light rays, was investigated as one of the phenomena that degrades photographic resolution. The investigation was experimental and consisted of making photographs of a resolution target through a supersonic wind tunnel with an Exacta high resolution camera (35mm film, f = 135mm, 1:2.8). Short-duration flash or long-exposure incandescent illumination was used and photographs were made when the wind tunnel was operating and when not operating. Under experimental test conditions the system gave an average resolution of 380 lines/mm when the tunnel was not running and gave an average resolution of 302 lines/mm when the tunnel was operated with speeds of Mach 1.5, 2.0, and 2.5 and pressures corresponding to 30,000 ft and 50,000 ft altitude. The loss in resolution of approximately 80 lines/mm corresponds to a stochastic influence of a boundary layer of about 1/3-inch thickness on light scattering and as if produced through a medium with an inherent resolution limit of 1500 lines/mm. The results are in fair agreement with NACA results. It was concluded that photographic systems with a resolution up to 100 lines/mm and usual aperture ratios may not be disturbed greatly by a thin turbulent boundary layer.

PUBLICATION REVIEW

This report has been reviewed and is approved for publication.

FOR THE COMMANDER:

W. S. Heavner

W. S. HEAVNER
Colonel, USAF
Chief, Reconnaissance Laboratory

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INTRODUCTION

From our knowledge of the different interactions between light and matter, we can expect the resolution of an aerial photographic camera to be limited by the influence of the fast flowing air, with its varying density, along a vehicle in supersonic flight (up to Mach 5). The magnitude of the effects on resolution is still not known, despite a number of theoretical and experimental efforts.

Some of the work already accomplished has been documented in References (1) through (9). The results given in these references show both similarities and dissimilarities. In any event, the works of these authors are of direct importance in developing a numerical solution for determining the degradation of photographic resolution which occurs when a supersonic airflow intervenes between the object being photographed and the camera being used.

Although available literature did not provide adequate background information on the problem, from these references and from the phenomena discussed in this report, we can consider that the influence of supersonic flow on photographic resolutions up to 30 lines/mm is negligible. But for the higher resolutions that are demanded in future aerial photographic developments, no answer has been given. A rigorous application of the results reported in References (3), (4), and (8) indicates that there is a definite resolution limit at about 60 lines/mm for commonly used aperture ratios under normal flight conditions. But one later report (Ref. 9) summarizes the state of the art and raises doubts as to the accuracy of the conclusions drawn in previous reports. Hence, the questions remain. Is a resolution of 60 lines/mm a final limit -- is this limit too low or too high -- where is the final limit?

Since the photographic resolution must be considered as a stochastic process (Ref. 10), a definite limit should be distinguished from a percentual influence that depends on the entire resolution of the optical system (object, medium, window, lens, and film).

In our study and experiments, we have cautiously shifted the resolution limit, caused by the supersonic airflow, to 100 lines/mm. We have assumed that a camera development having common aperture ratios up to this value is justified. The final actual limit, which might be higher than 100 lines/mm, was not determined. A great deal more work is necessary before the true limit can be found.

THE DEGRADATION PROBLEM IN GENERAL

DEGRADING PHENOMENA.

The main phenomena responsible for the degradation of aerial photographs are:

a. Refraction, dispersion, and scattering of the light rays caused by different density and turbulence of the air flow.

b. Diminishing of contrast, due to possible luminosity of the air surrounding the aircraft (especially true under hypersonic conditions).

c. Distortion of the optical equipment caused by heat generated by air friction.

In this report, we have limited our investigations to the phenomena in category "a" because we believe that the problems of category "b" are based on different physical phenomena and that the problem of category "c" can be minimized by proper design.

RESOLUTION PROBLEMS

The resolution of an optical system in the image plane is not determined by geometrical optics alone, it is finally limited by diffraction. Since the diffraction pattern is influenced by the scattering of light in front of the optics, we must investigate the phenomena.

The diffractive resolution limit of a system is given by the Rayleigh criterion, which is derived from the distribution of intensity in the diffractive pattern of the Airy disc. The diffractive pattern of an Airy disc is the imaged diffraction figure that is obtained from a light-emitting point-source by the shape and size of the aperture. The angular distance of the dark fringes in the diffractive disc, as seen from the second nodal point of the objective, is given by

$$\mathrm{Sin}\ \gamma_i = \frac{\lambda w_i}{D}$$

where w_i has values 1.220, 2.233, 3.238, and 4.241, respectively, and D is the entrance pupil diameter, being of circular shape. The illumination in the Airy disc is

$$E = \frac{\pi}{4} D^2 \psi$$

and the average brightness of the central disc is

$$B = \frac{\psi}{(2.44\lambda)^2} \quad \frac{D^4}{F^2}$$

where ψ is the transmission-coefficient of the objective, and F is its focal length. Two adjacent object points can be sufficiently separated in their image only when the center of the diffraction disc of one image point coincides at least with the first dark fringe of the other. This condition is the well known Rayleigh-criterion and yields

$$\gamma_i = \frac{1.22\lambda}{D}$$

for the limit of resolution of a given objective when the objective is considered free of any other aberrations.

The ultimate value for the resolution in the focal surface of the image space is valid only for the above conditions. Theory shows that these conditions, if changed, alter the ultimate resolution according to the relation

$$B = \frac{C^2 + S^2}{\lambda^2 \ \xi^2}$$

where C and S are two complicated integrals and ξ is the distance from exit pupil to image point. (See References 18 and 19.) A magnitude Z is defined by

$$Z = \frac{2\pi p d}{\lambda \xi} \quad \left(\begin{array}{l} p = \text{radius of exit pupil} \\ d = \text{distance image point to optical axis} \end{array} \right)$$

for which a difference exists, whether the light entering the objective is coherent or not. A light-emitting object usually will be an incoherent source, while a diffuse reflecting object acts as a coherent one since all elementary wavelets start with equal phase. Hence, the rays coming from reflecting objects are able to interfere with each other. This enlarges the Airy disc and lowers the resolution. The enlargement, for example, increases in the same way as the theoretical value for Z increases from 2.9 to 4.6, whether the object emits or reflects light. When the aperture has a rectangular opening instead of a circular one, those two values for Z for emitted and reflected light become somewhat better, i.e., 2.8 and 4.2, respectively.

From astronomy, we know that the Rayleigh-criterion has to be multiplied with a factor σ to get the resolution values that are really observed through the earth's atmosphere. The factor σ is called the atmospheric scintillation factor. The diameter of the central diffraction disc is then given by

$$p = F \sigma \sin 1'' .$$

Hence, the resolution becomes dependent on the focal length and it could be shown that σ depends on the diameter of the aperture, also. Values for σ range from 1 to 8 arc-seconds for quiet to very distrubed atmospheric conditions. From this, we see the influence of weak turbulences on the diffractive pattern which finally determines the resolution. Likewise, the influence of selective chromatic changes by the atmosphere, called the extinction, has been studied. It is clearly indicated that the preference for certain wave lengths being transmitted through the atmosphere changes randomly. Therefore, the changes in resolution, being influenced by this factor, are proportional to the wave length and are caused by an alternating dispersion of the turbulent air eddies. (See Reference 20.) Moreover, astronomers have studied carefully the difference in resolution for stars (light emitting point sources) and planets (light reflecting extended sources) and have found that the resolution of the latter is lower, as should be expected from the preceding explanations.

INFLUENCE OF THE SHOCK WAVE PATTERN

References (1) and (11) show that we can expect considerable deviations of light beams due to the shock-wave pattern, alone; similar indications are given in Reference (2). The refractive index N depends on the density of air in the form

$$N = 1 + \frac{\rho}{\rho_o} (N_o + 1)$$

where ρ_o and N_o are the density and the absolute refractive index of "normal air." The absolute refractive index of air again depends on its pressure p and temperature t in the form

$$N_{t,p} = 1 + \frac{(N_{o,760} - 1) \cdot p}{(1 + t) \cdot 760}$$

For the wavelength λ_D = 5893 Å, sea level pressure 760 mm Hg, and room temperature +20°C, the value for N_o is $N_{o,760}$ = 1.00027. The density of atmospheric air depends on the altitude H (in meters) of observation in the form

$$\rho_H = \rho_o \times 10^{-0.000045 \times H}$$

which represents the density of the undisturbed flow in that altitude, while the density behind a shock wave in a flow being disturbed by a rotationally symmetrical vehicle with conical nose in supersonic speed is given as ratio $\frac{\rho}{\rho_H}$, depending on the Mach number. The ratios for Mach numbers 1.0, 1.2, 1.5, 2.0, 3.0, and 5.0 have the values 1.00, 1.34, 1.86, 2.66, 3.83, 4.96, and 5.94, respectively, and this means a corresponding change of refractive index $N_{t,p}$ with the Mach number.

The light rays entering the camera window arrive from different points of the object's area under different angles-of-view, depending on the altitude of the aircraft and the field angle-of-view, and every object point reflects or emits a pencil of rays which can be considered to be parallel, i.e., of cylindrical shape, before it enters the shock wave. The wave front surface from every object point, therefore, is a plane.

The shock wave, with its zones of rarefaction and compression behind it, forms in the region of the camera window a partial sector of a conically-shaped gaseous medium with anisotropic discontinuous change of refractive index. This conical sector will bend the light rays in a three-fold manner:

1. It will bend all the pencils of rays from the different object points an approximately equal amount causing only a sighting error in the direction of the camera, hence being relatively unimportant for aerial photography.

2. Every pencil of the different object points will suffer an individual bending that will be different than that for any other pencil because of the different angle of incidence into the cone and the individual-density distribution. This effect will distort the relative position of the image points if compared with the object points and, therefore, will lower resolution in some or all areas of the image.

3. Within the cross section (diameter of entrance pupil) of every pencil, every ray will suffer a smaller individual bending that will be unlike the bending of any other ray. This variation in bending will occur because of the reason given in sub-paragraph 2. This effect will cause an unproportional illumination and an enlargement of the corresponding image point and, therefore, will lower the overall resolution and the contrast.

Contrary to the usual assumptions, the anistropic cone cannot be considered as exhibiting constant values of refraction with time. The gases are in a turbulent and laminar state which will show a fast change of the density pattern with time. We will call this effect "fluctuations." The maximum values of these fluctuations and their duration are unknown at present and should be determined by wind-tunnel tests.

If we are to describe the optical wave front after it has passed the distrubed flow field, we must know the absolute density distribution in that field in all three dimensions. Interferometric measurements, calculations based on supersonic aerodynamics, and, to a certain degree, Schlieren-pictures supply those values when made with the purpose of obtaining the density distribution alone and not in combination with other parameters. A special and promising method for this goal is the use of X-rays to obtain spotwise measurement of the density distribution in the disturbed flow (briefly described in Ref. 12).

Since the angle of incident entering the shock-wave pattern is of great importance according to the refractive law, the study of the mentioned effects for various directions-of-view with respect to the shock wave will supply data for the most suitable conditions (Ref. 1). The location of the camera in the airplane, the angle-of-view of the camera, and the shape of the shock-wave pattern can be altered to achieve the best result. Wave-front surfaces which deviate the least from a plane when entering the boundary layer of the entrance pupil and which have the smallest chromatic aberration under equal angles of acceptance from every object point give the best results.

INFLUENCES OF THE BOUNDARY LAYER

Even if the wave front entering the boundary layer has been made or is plane or nearly plane, it must penetrate this layer. Therefore, we encounter an additional resolution-lowering effect. Reference (13), (3), and (9) show that light penetrating a gas layer which is in turbulent motion suffers a remarkable amount of scattering and, in the case of oblique incidence, will deviate from its original direction. In the references, the problem is approached either theoretically or experimentally. Although certain agreements between calculated and observed values have been achieved, we can see that the physical problems are far from being solved.

For an explanation of the phenomena in question, we must refer to the original works of Lord Rayleigh (Ref. 14), A. H. Lorentz (Ref. 15), and A. Einstein (Ref. 16), and to the different steps of the classical and quantumstatistical development of the theory of dispersion presented in detail by Sommerfeld in Reference (17).

According to Sommerfeld, the molecules of the gas, by their own electrical field give rise to a value of the dielectrical constant within a volume. This value may be, for instance, smaller than the wave length of light, and is a value which is subject to statistical oscillations, depending on the vibrations of the molecules. If ϵ_0 is the mean value of the dielectrical constant and $\Delta\epsilon$ is its oscillation value, the Maxwell equations for the incident light wave (first considered polarized and monochromatic) change to

$$C \operatorname{rot} \dot{H} = \epsilon \frac{\partial E}{\partial t} + \Delta\epsilon \frac{\partial E}{\partial t} \quad ; \quad -C \operatorname{rot} E = \frac{\partial H}{\partial t}$$

The interaction of the incident light wave with the electrons belonging to the molecules must be imagined as a forced vibration of the electrons, which by themselves become the sources for new waves. The introduced phase shift between electric and magnetic vectors of the incident wave results in a spreading out of the Poynting vector for the new wave as function of angle θ against the direction of the primary wave. Because a spread Poynting vector means scattered energy, the Poynting vector for the flow of energy becomes

$$\overline{S} = J_0 \left(\frac{\Delta\epsilon\, d\tau}{4\pi r}\right)^2 \left(\frac{2\pi}{\lambda_0}\right)^4 \sin^2\theta$$

where J_o is the primary intensity, r the distance from the place of observation to the small volume $d\tau$, and θ the angle of scattering. Since the forced vibrations of the electrons consume some of the incident energy, a certain absorption can be inferred by this process, which will be a selective one, if the incident light waves are polychromatic and are related to the electronic configurations in the volume $d\tau$ by certain modes. The absorption coefficient for the process becomes

$$\alpha = \frac{8\pi^3}{3} \frac{(\overline{\Delta\epsilon})^2 \, d\tau}{\lambda_o^4}$$

where $(\overline{\Delta\epsilon})^2$ is called the mean square of oscillations of the dielectrical constant. It is given by

$$(\overline{\Delta\epsilon})^2 = \left(\frac{\partial\epsilon}{\partial\rho}\right)^2 (\overline{\Delta\rho})^2$$

where ρ now means the density of the gas, and $\Delta\rho$ the density variation. For the scattered radiation when the intensity rectangular to the incident intensity is called I_o,

$$J = \frac{\pi^2 \, d\epsilon}{18\lambda^4 \, r^2 \, N} J_o (n^2 - 1)^2 \frac{1 + 2\vartheta}{1 - \frac{\vartheta}{6}}$$

with N as the number of molecules, n the refractive index, and ϑ the so-called degree of depolarization. In an actual case, the volume to be considered is large if compared with the wave length, therefore, the scattered wave will form a new vibration in neighboring elementary volumes, and so on and waves which are generated closely enough to be coherent to each other will undergo interference effects that increase the chromatic selectivity in a specific direction.

LIMITATIONS IN BACKGROUND LITERATURE AND PREVIOUS EXPERIMENTS

Although the preceding explanations of the conditions that affect resolution were brief, they do seem to indicate that the knowledge about all physical phenomena that must be considered when solving the general problem is already rather comprehensive. We might think that a rough calculation of the ultimate resolution that is dependent on different flight conditions might be made by using the data in the references. But knowledge is not comprehensive enough for us to make even rough calculations.

Reference (1) is related mainly to the bending of a direction of view through the shock-wave pattern. The given refractions range from a few arcseconds to even arc-minutes, but only a general structure of the disturbed flow field is assumed. Cancellations of these bendings in the pattern are expected. Fluctuations and scattering are not considered.

Reference (11) shows that the blurring of photographs can become disastrous.

Reference (2) discusses experiments performed, but the experiments were not accurate enough for our purpose. Conclusions indicate image deterioration for supersonic speeds. Numerical evaluation is not possible.

Reference (12) shows considerable jumps or density within and behind the shock-wave.

References (4), (8), and (9) all give measurement information on the scattering by wind-tunnel boundary layers. All show enlargement of the Airy disc connected with dissipation of light energy into lateral directions by scattering dependent upon the supersonic air speed. The measured results show that a serious degradation of resolution occurs. (Some data are not mentioned here due to the classification of one of the references.) To arrive at valid conclusions for our specific problem, we must make experimental arrangements.

Reference (3) concludes, on theoretical grounds, that the light diffusion can reach several arcseconds and that considerable bending of obliquely incident beams by the boundary layer can occur. The results are fairly general and, therefore, a considerable amount of detailed work remains to be done.

References (21) and (22) are of great value for the theoretical understanding of the physical processes. The works are related to scattering of electro-magnetic waves of much greater wave length than light. Conclusions for light waves are, therefore, only allowed as far as the involved analogies are valid.

Although we can assume that light scattering in the turbulent boundary layer is the phenomenon that is the chief contributor to the expected image deterioration for supersonic flight speeds (Mach 1.5 to 4), we cannot consider the problem solved. We even question whether or not we can bluntly apply the results of References (4) and (8), which were integrating energy measurements. Because of our doubts, we started new experiments at Aeronautical Systems Division (ASD).

ASD WIND-TUNNEL EXPERIMENTS

A direct photographic wind-tunnel experiment was set up in the usual way, but with equipment of such extreme sensitivity that the direct influence of the turbulent boundary layer on photographic resolution could be studied.

The influence of diffuse refraction by shock wave and the density fluctuations in the shock cone seem to be of second order importance and were not investigated during the wind-tunnel experiments.

EXPERIMENTAL INSTRUMENTATION AND TEST PROCEDURE

Figure 1 shows the test setup arrangement of the experimental instrumentation. On an optical bench 0 a photo flash bulb S, or incandescent lamp, illuminated a standard-resolution target T which was in the focal plane of a collimating objective L; the collimated light beams penetrated the windows and the air flow of the otherwise empty wind tunnel W and were photographed by a high resolution camera C on 35-mm film F. The sturdy bench (65 inches long) was fully insulated against vibration from the tunnel. The flash bulb (a Xenon-filled helical tube type) could be triggered by four different capacitors (28, 56, 84, and 112 MF) with a duration of 1/2 to 1-1/4 milliseconds. A replica, on glass, of Resolving Power Test Targets USAF 1951 was used as a target. The collimating objective was a Zeiss-Apo-Tessar having a 90-cm focal length and an f:9 aperture. The camera was an Exacta (35-mm) from Zeiss-Ikon, Dresden, East Germany, with a Steinheil objective of 135-mm focal length and an f:2.8 aperture. The camera was fixed on the bench. Between light source and target, we could insert spectral filters. The photographs were taken on 548C (Kodak) film. This test setup gives, in the laboratory, the excellent mean value of 426 lines/mm, and sometimes comes close to the Rayleigh-limit, which is 525 lines/mm for $\lambda = 5500 \text{Å}$.

The wind tunnel was the six-inch by six-inch supersonic continuous flow tunnel located in the Aircraft Laboratory at Aeronautical Systems Division. Detailed information about this tunnel has been given in Appendix B.

For the purpose of comparison, pictures were taken when the wind tunnel was in operating and in non-operating conditions. The tunnel operated at speeds of Mach 1.5, 2.0, and 2.5, and with the different pressures that correspond to altitudes of 30,000 feet and 50,000 feet. At those speeds and pressures, the tunnel generates a turbulent boundary layer of approximately 1/3-inch thickness for each window along the test section of windows.

In the photographic equipment, the time of exposure and the color of the light were changed. The pictures were taken by flashing or switching the light and not by operating the shutter.

A total of 56 photographs were taken through the wind tunnel, with or without windows, when the tunnel was not operating. When the wind tunnel was running at various Mach numbers, 121 photographs were taken through the tunnel. Each photograph was examined through a microscope having a 280 magnification.

TEST RESULTS

Tables 1 through 16 were developed from the 177 photographs taken under test conditions and give the observed resolution of each picture. In the tables, the first column is the sequential exposure number of pictures for one film strip. The second column shows the filter used. In this column, "None" means no filter; "N", a neutral density filter; "Y", a yellow (Wratten No. 6); "Q", a green (Wratten No. 58); "B", a blue gelatine (Wratten No. 45). The third column shows the figures 28, 56, 84, and 112. These figures indicate the capacity in MF for operating the flash bulb -- they indicate how long, in milliseconds, the film was exposed (see curves in Figure 2). The fourth column is the just resolvable index number of the target. The reader should understand that every possible precaution was taken to prevent bending and swelling effects of the film in the focal plane of the microscope. The other columns in the tables are self-explanatory. The column headed "Factor" presents the corresponding lines/mm for unity magnification and those values have to be multiplied by 6.6, the ratio $\frac{\text{focal length of the collimator}}{\text{focal length of the camera}}$, to get the actual lines/mm given in the last column.

Our evaluation of the pictures was based on what the 280X microscope revealed. We found that the index number of the just resolvable target for small area extensions of approximately 1/15,000 mm^2 was strongly dependent on slight variations in film blackening and that the targets with such small index numbers as 5.1 to 6.6 were underexposed when the larger targets were correctly exposed. Therefore, a picture had to be overexposed in general appearance in order to show the highest resolution. This strong correlation between high resolutions and blackening values makes absolute accuracy doubtful, but, of course, it does not destroy the validity of resolution index numbers which are always reached with certainty.

We found no deterioration of resolution that could be attributed to windows of the tunnel. During a run, an oil film always appeared inside the window, and this lowered the resolution somewhat. Hence, the windows had to be cleaned after nearly every run. A difference between the incandescent and the flash illuminations can be seen from the tables of data. We might think that this difference was due to vibrations, since the incandescent exposures were 4 seconds and the flash exposures were only 1/2 to 1-1/4 milliseconds. But the exposures made with incandescent light through the tunnel when it was not running show a lower resolution, too. Whether this is, therefore, an effect of coherence (flash) and incoherence (incandescent) or the time effect of blackening by scattering remains to be proven. Pictures taken through the yellow filter yielded the highest achievable resolution.

All pictures taken through the wind tunnel, with or without windows, but in non-running condition show a natural scatter of index number measurements, which is grouped on a bell-shaped curve (Figure 3) with its maximum at 380 lines/mm. This value is lower than that given previously because of the blackening effect. If we use only the pictures of higher blackening, 400 to 426, and even 478 to 532 lines/mm are achieved. The range of measurement scatter then is from 302 to 478, i.e., 176 lines/mm (±25%) (see Curve I of Figure 3).

All pictures taken through the wind tunnel when it was in running condition, regardless of Mach number, show a natural measurement scatter. This scatter is also grouped on a bell-shaped curve (see Figure 3) with its maximum at 302 lines/mm and a scatter from 240 to 380, i.e., 140 lines/mm, or from 213 to 425, i.e., 273 lines/mm. Hence, the mean scatter is again 173 lines/mm and this curve is nearly congruent to the first curve, indicating a true shift of the most probable values from 380 lines/mm for a condition of an undisturbed medium to 302 lines/mm for a condition of turbulent supersonic flow between collimator and camera. Hence, the running tunnel causes a lowering of resolution of approximately 80 lines (20%). (See Curve II of Figure 3.) We see from the tables that the scatter of measurements is so large that a distinction between Mach numbers or altitudes cannot be made.

Empirically, the recognizable information on a film in a photographic process (which for high-contrast black-white line targets is given in lines/mm) can be presented as the sum of the reciprocal single resolutions of all the influencing media. It is

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \;---$$

with

R_1 = resolution of lens

R_2 = resolution of film

R_3 = resolution of medium.

This corresponds to the fact that in the entire optical process, from object to picture, the action of the single elements is not a rigid casual one, but, according to informational theory, is one that is only weighted with a certain probability. It is a so-called stochastic process. The influence of the turbulent flow on the resolution of the used camera then becomes

$$\frac{1}{302} = \frac{1}{380} + \frac{1}{X}$$

with $X = 1470$.

With regard to the wide scatter of measurements, in relation to the special case of our experiment, we can say that the turbulent supersonic boundary layer acts like a medium with an inherent resolution limit of approximately 1500 lines/mm. As was pointed out previously, the influence of the shock wave and the shock cone is not considered, yet it might be of a similar magnitude. Furthermore, in theory, an increasing turbulent boundary layer influence can be expected with an increase in the diameter of the lens, an effect which could not be investigated during the ASD experiments. However, since other resolution-limiting factors also increase when the diameter of the lense is increased, and since the aerodynoptical influence for a 100 lines/mm system would only amount to approximately 12% under the close-to-reality conditions given in the ASD experiment, the conclusion given in the introduction seems to be justified.

Moreover, Table 16 indicates that for different overall resolution of the system the boundary layer shows a stochastic influence, too. The system resolution was artificially lowered by defocusing the collimator. The resolution dropped to about 320 lines/mm for non-running tunnel, and to 268 lines/mm for running tunnel. The influence, again, is like that of a medium with about 1500 lines/mm.

CONCLUSIONS

After reading References (4) and (8), one would expect a stronger influence than that derived by the experiments. The reported investigations, although having quite a different purpose than our experiments, give also a derived mathematical relation which can be directly applied to our results. For constant air-flow conditions, the relation shows that the resolution, by the influence of the turbulent scattering, decreases with an increase of the camera's lens diameter. Since, according to Rayleigh, the resolution is limited by diffraction increases with the lens diameter, both effects nearly compensate each other. If we used values from Reference (8) for aperture ratios f:6, f:8, and f:22, the limit would be always 60 lines/mm for Mach 2.0 at 45,000 ft altitude when there was a boundary layer 1-3/4 inches thick. In our experiment, the optical and wind-tunnel conditions are somewhat different; the diameter of the lens is only 48mm as compared with 63mm of Reference (8), i.e., 20% smaller. If we then assume an effective wavelength $\lambda = 5500\text{Å}$ and use the theoretical Rayleigh limit of 525 lines/mm, a degradation factor of 1.7 would result. The boundary layer thickness for our wind tunnel experiment is not accurately known; it is assumed from other experiences to be only 1/3 inch, hence, by including the other wind tunnel parameters, an agreement between the measurements of Reference (8) and our own can easily be construed. Furthermore, for short-time flash exposures, only the peak central part of the Airy disc will act. This action will be according to the color-selective gradation curve of the film and will be only with that bandwidth of wavelengths which is produced by the temperature of highest excitation during the peak time of the flash. The degrading rays produced by scattering, therefore, will be less effective, and the resolution will be higher than expected at first glance.

The results are in fair agreement with NACA results. We conclude that photographic systems with a resolution up to 100 lines/mm and usual aperture ratios may not be disturbed substantially by a thin turbulent boundary layer. These conclusions, however, are not satisfying. More accurate data, with less scatter in measurement values and better knowledge of actual wind-tunnel conditions are necessary.

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APPENDIX A

ILLUSTRATIONS AND TABLES

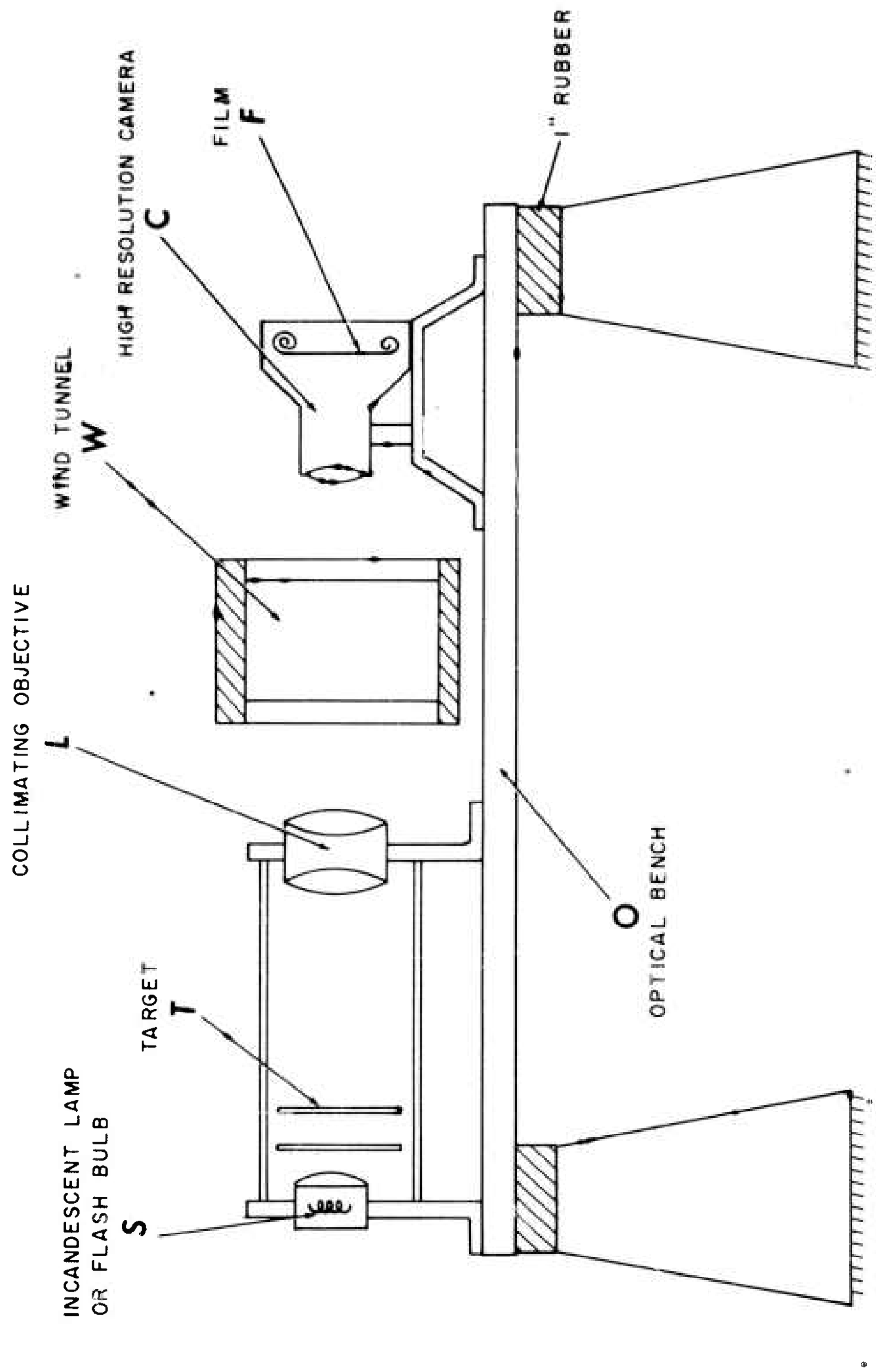

Figure 1. Bench Test Setup

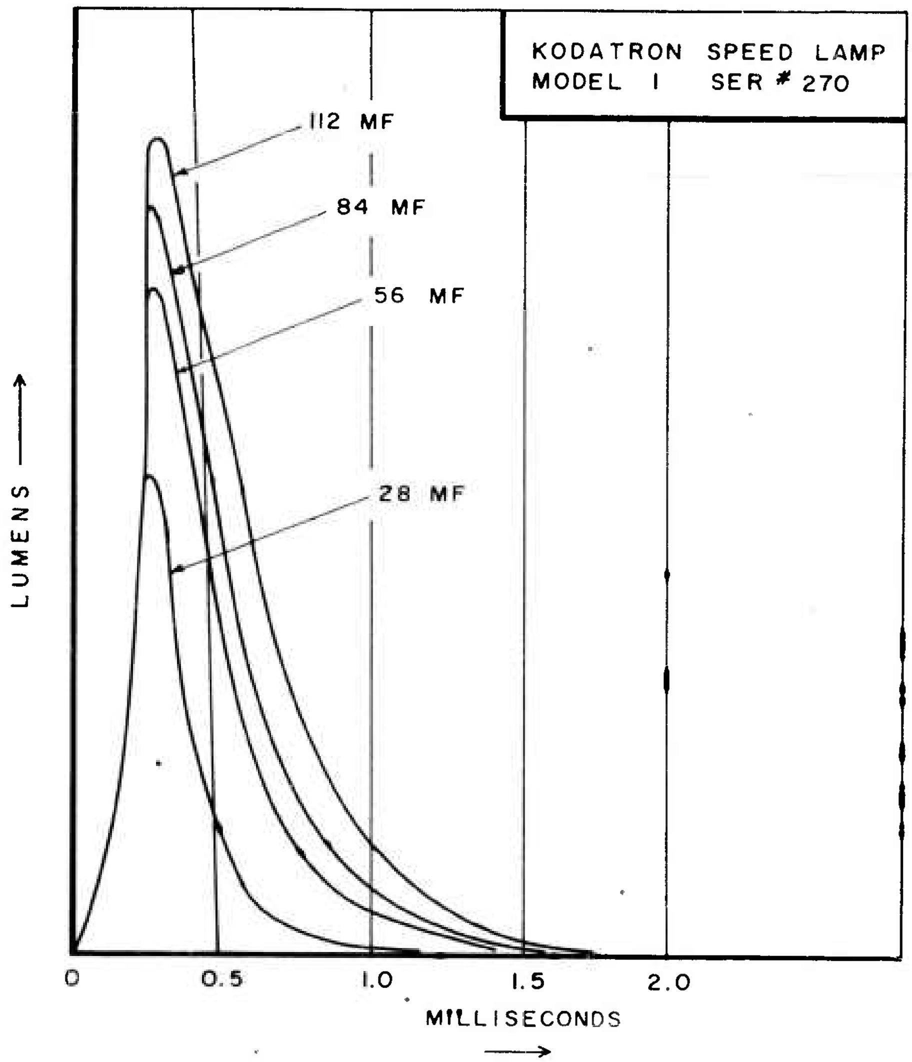

Figure 2. Exposure Times of Speed Lamp Versus Capacitor Setting

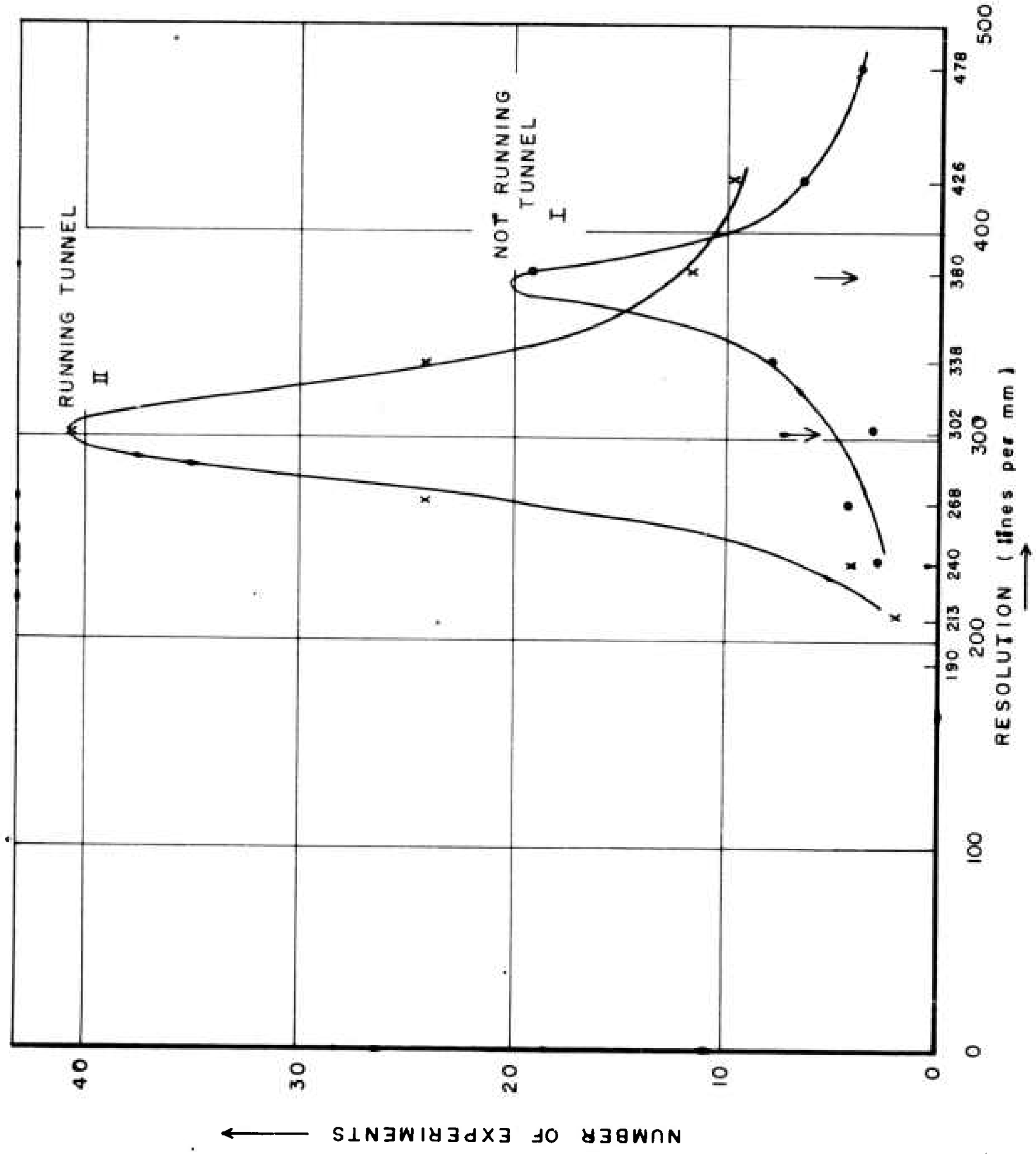

Figure 3. Measured Resolution Data

TABLE 1

NUMERICAL DATA -- TUNNEL NOT OPERATING, NO WINDOWS
Film Identification 1 - 25

Sequential Exposures on Film Strip	Filter	Capacity in MF for Operating Flash Bulb	Resolvable Index of Target	Remarks	Corresponding Line/mm for Unity Magnification	Actual Lines/mm
1	Y	28	5.4	Not clean, many scratches	45.3	302
2	G	28	0.0	Exposure too weak		
3	B	28	0.0	Exposure too weak		
4	Y	56	6.2	Excellent	71.8	478
5	G	56	5.2	Faint exposure scratches	36.0	240
6	B	56	0.0	Exposure too weak		
7	Y	84	5.6	Good	57.0	380
8	G	84	5.3	Faint exposure	40.3	268
9	B	84	5.2	Too faint	36.0	240
10	Y	112	6.1	Very good, but scratches	64.0	426
11	G	112	6.1	Very good	64.0	426
12	B	112	5.5	Faint exposure	50.8	338
13	Y+N	28	0.0	Exposure too weak		
14	Y+N	56	0.0	Exposure too weak		
15	Y+N	84	5.5	Faint exposure	50.8	338
16	Y+N	112	5.3	Too faint	40.3	268

TABLE 2

NUMERICAL DATA -- TUNNEL NOT OPERATING, ONE WINDOW
Film Identification 2 - 25

Sequential Exposures on Film Strip	Filter	Capacity in MF for Operating Flash Bulb	Resolvable Index of Target	Remarks	Corresponding Line/mm for Unity Magnification	Actual Lines/mm
1	Y	28	5.6	Fair exposure	57.0	380
2	G	28	0	Exposure too weak		
3	B	28	0	Exposure too weak		
4	Y	56	6.2	Excellent	71.8	478
5	G	56	4.1	Very faint	16.0	106
6	B	56	0	Exposure too weak		
7	Y	84	6.3	Excellent, may be 6.2	80.6	532
8	G	84	5.2	Very faint	36.0	240
9	B	84	4.3	Very faint	20.2	135
10	Y	112	6.2	Excellent	71.8	478
11	G	112	5.6	Very good	57.0	380
12	B	112	5.3	Faint	40.3	268
13	Y+N	28	0	No exposure, very weak		
14	Y+N	56	0	Exposure too weak		
15	Y+N	84	0	Exposure too weak		
16	Y+N	112	0	Exposure too weak		

TABLE 3

NUMERICAL DATA -- TUNNEL NOT OPERATING, TWO WINDOWS
Film Identification 3 - 25

Sequential Exposures on Film Strip	Filter	Capacity in MF for Operating Flash Bulb	Resolvable Index of Target	Remarks	Corresponding Line/mm for Unity Magnification	Actual Lines/mm
1	Y	28	5.4	Faint	45.3	302
2	G	28	0	No exposure, very weak		
3	B	28	0	No exposure, very weak		
4	Y	56	6.1	Excellent	64.0	426
5	G	56	4.3	Very faint	20.2	135
6	B	56	0	Exposure too weak		
7	Y	84	6.1	Excellent, may be 5.6	64.0	426
8	G	84	0	Weak exposure full of scratches		
9	B	84	0	Exposure too weak		
10	Y	112	6.1	Excellent, may be 6.2	64.0	426
11	G	112	5.6	Good	57.0	380
12	B	112	4.5	Faint	25.4	169
13	Y+N	28	0	No exposure, very weak		
14	Y+N	56	0	Exposure too weak		
15	Y+N	84	0	Exposure too weak		
16	Y+N	112	0	Exposure too weak		

TABLE 4

NUMERICAL DATA -- TUNNEL NOT OPERATING, TWO WINDOWS
Film Identification 4 - 25

Sequential Exposures on Film Strip	Filter	Capacity in MF for Operating Flash Bulb	Resolvable Index of Target	Remarks	Corresponding Line/mm for Unity Magnification	Actual Lines/mm
1	None	28	5.6	Good	57.0	380
2	None	28	5.6	Good	57.0	380
3	None	28	5.6	Good	57.0	380
4	N	28	0	Exposure too weak		
5	N	28	0	Exposure too weak		
6	N	28	0	Exposure too weak		
7	N	56	4.4	Very faint	22.6	150
8	N	56	4.4	Very faint	22.6	150
9	N	56	4.4	Very faint	22.6	150
10	N	84	5.6	Faint	57.0	380
11	N	84	5.5	Faint, many scratches	50.8	338
12	N	84	5.4	Faint, many scratches	45.3	302

TABLE 5

NUMERICAL DATA -- MACH 1.5, HIGH PRESSURE
Film Identification 1 - 26

Sequential Exposures on Film Strip	Filter	Capacity in MF for Operating Flash Bulb	Resolvable Index of Target	Remarks	Corresponding Line/mm for Unity Magnification	Actual Lines/mm
1	Y	28	5.1	Very good	32.0	213
2	G	28	0	Exposure too weak		
3	B	28	0	No exposure, very weak		
4	Y	56	5.3	Excellent	40.3	268
5	G	56	0	Exposure too weak		
6	B	56	0	No exposure, very weak		
7	Y	84	5.5	Excellent, Corresponds to 2-25, 7	50.8	338
8	G	84	5.2	Good, but faint	36.0	240
9	B	84	0	Exposure too weak		
10	Y	112	5.4	Overexposed	45.3	302
11	G	112	5.3	Good, but faint	40.3	268
12	B	112	5.3	Good, but faint	40.3	268

TABLE 6

NUMERICAL DATA -- MACH 1.5, HIGH PRESSURE
Film Identification 2 - 26

Sequential Exposures on Film Strip	Filter	Capacity in MF for Operating Flash Bulb	Resolvable Index of Target	Remarks	Corresponding Line/mm for Unity Magnification	Actual Lines/mm
1	None	28	5.3	Very good some scratches	40.3	268
2	None	28	5.1	Many streaks probably 5.2	32.0	213
3	None	28	4.6	Good	28.5	190
4	N	28	0	Exposure too weak		
5	N	28	0	Exposure too weak		
6	N	28	0	Exposure too weak		
7	N	56	0	Exposure too weak		
8	N	56	0	Exposure too weak		
9	N	56	0	Exposure too weak		
10	N	84	4.6	Good	28.5	190
11	N	84	4.5	Faint (good)	25.4	169
12	N	84	4.4	Faint (good)	22.6	150
13	N	112	4.3	Faint (good)	20.2	134
14	N	112	4.3	Faint many scratches	20.2	134
15	N	112	4.3	Good	20.2	134

TABLE 7

NUMERICAL DATA -- MACH 1.5, HIGH PRESSURE
Film Identification 1 - 29

Sequential Exposures on Film Strip	Filter	Capacity in MF for Operating Flash Bulb	Resolvable Index of Target	Remarks	Corresponding Line/mm for Unity Magnification	Actual Lines/mm
1	None	28	5.3	Good	40.3	268
2	None	28	0	Typically blurred picture		
3	None (Tunnel not operating)	28	5.6	Very good	57.0	380
4	None	28	5.3	Strongly exposed vertical stripes	40.3	268
5	None	28	5.2	Faint	36.0	240
6	None	28	5.4	Good	45.3	302
7	None	56	5.4	Very good	45.3	302
8	None	56	5.5	Very good	50.8	338
9	None	56	5.6	Very good	57.0	380
10	N	84	0(5.4)	Exposure too weak		
11	N	84	0	Exposure too weak		
12	N	84	0(5.4)	Exposure too weak		
13	N	112	5.3	Faint	40.3	268
14	N	112	0(5.3)	Very faint		
15	N	112	5.4	Good (faint)	45.3	302
16	Y	112	6.1	Overexposed vertical stripes	64.0	426
17	G	112	5.4	Faint	45.3	302
18	B	112	0	Exposure too weak		

TABLE 8

NUMERICAL DATA -- MACH 1.5, LOW PRESSURE
Film Identification 2 - 29

Sequential Exposures on Film Strip	Filter	Capacity in MF for Operating Flash Bulb	Resolvable Index of Target	Remarks	Corresponding Line/mm for Unity Magnification	Actual Lines/mm
1	None	28	5.6	Very good	57.0	380
2	None	28	4.6	Good, but definitely blurred	28.5	190
3	None	28	5.4	Good	40.3	268
4	None	56	5.6 (6.1)	Very good	57.0	380 (426)
5	None	56	6.1	Excellent	64.0	426
6	None	56	5.6 (6.1)	Excellent	57.0	380 (426)
7	N	84	5.5	Faint	50.8	338
8	N	84	5.4	Very faint	45.3	302
9	N	84	0	Exposure too weak		
10	N	112	5.4	Faint	45.3	302
11	N	112	5.5	Faint	50.8	338
12	N	112	5.4	Faint	45.3	302
13	Y	112	6.1	Excellent	64.0	426
14	G	112	5.4	Faint	45.3	302
15	B	112	5.3	Very faint	40.3	268
16	None	28	5.6	Good	57.0	380
17	None	28	5.5	Good 5.6 disturbed	50.8	338
18	None (Tunnel not operating)	28	5.5	Good	50.8	338

TABLE 9

NUMERICAL DATA -- MACH 2.5
Film Identification 3 - 29

Sequential Exposures on Film Strip	Filter	Capacity in MF for Operating Flash Bulb	Resolvable Index of Target	Remarks	Corresponding Line/mm for Unity Magnification	Actual Lines/mm
*1	None	28	6.2	Very good	71.8	478
*2	None	28	5.6	Somewhat faint	57.0	380
*3	None	28	5.6	Somewhat faint	57.0	380
4	None	28	6.1	Very good	64.0	426
5	None	28	5.5	Faint	50.8	338
6	None	28	5.6	Very good	57.0	380
7	None	56	6.1	Very good	64.0	426
8	None	56	6.1	Very good	64.0	426
9	None	56	6.1	Very good	64.0	426
10	N	84	0(5.3)	Too faint		
11	N	84	0(5.5)	Too faint		
12	N	84	0(5.5)	Too faint		
13	N	112	5.6	Good	57.0	380
14	N	112	5.5	Good, distances between 5.3 and 5.4	50.8	338
15	N	112	5.4	Good to faint	45.3	302
16	Y	112	5.6	Excellent	57.0	380
17	G	115	0(5.3)	Too faint		
18	B	112	0	Exposure too weak		

* Tunnel Not Operating

TABLE 10

NUMERICAL DATA -- INCANDESCENT LIGHT 150 WATT #212 PHOTOENLARGER OPAL; MACH 2.5
Film Identification 4 - 29

Sequential Exposures on Film Strip	Filter	Exposure	Resolvable Index of Target	Remarks	Corresponding Line/mm for Unity Magnification	Actual Lines/mm
1	None	1 sec	0	Exposure too weak		
2	None	2 sec	5.4	Faint	45.3	302
3	None	3 sec	5.3	Faint to good	40.3	268
			(4)			(302)
4	None	4 sec	5.4	Very good	45.3	302
5	None	5 sec	5.4	Very good	45.3	302
6	None	6 sec	5.4	Excellent	45.3	302
7	None	7 sec.	5.4	Overexposed, vertical stripes and vertical lines better than horizontal	45.3	302
8	None	8 sec	5.4	Effect like 7, but stronger	45.3	302
9	None	9 sec	5.3	Effect like 7, but stronger than 8	40.3	268
10	None	10 sec	5.2	Effect like 7	36.0	240
11	None	30 sec		Extreme overexposure		

TABLE 11

NUMERICAL DATA -- MACH 2.0, HIGH PRESSURE
Film Identification 5 - 29

Sequential Exposures on Film Strip	Filter	Capacity in MF for Operating Flash Bulb	Resolvable Index of Target	Remarks	Corresponding Line/mm for Unity Magnification	Actual Lines/mm
*1	None	28	5.5	Good	50.8	338
*2	None	28	5.6	Very good - vertical better than horizontal	57.0	380
*3	None	28	5.5	Very good - like 2	50.8	338
4	None	28	5.5	Very good - like 2	50.8	338
5	None	28	5.6	Very good - like 2	57.0	380
6	None	28	5.5	Very good - like 2	50.8	338
7	None	56	5.5	Excellent - vertical 5.6 better than horizontal	50.8	338
8	None	56	5.6	Excellent - vertical 6.1; horizontal 5.5	57.0	380
9	None	56	5.5	Excellent - vertical 5.6; horizontal 5.4	50.8	338
10	N	84	5.4	Faint	45.3	302
11	N	84	5.3	Very faint	40.3	268
12	N	84	5.3	Faint	40.3	268
13	N	112	5.4	Faint	45.3	302
14	N	112	5.4	Faint - vertical 5.5; horizontal 5.3	45.3	302
15	N	112	5.4	Faint	45.3	302
16	Y	112	5.5	Excellent - vertical 5.6; horizontal 5.5	50.8	338
17	G	112	5.4	Faint	45.3	302
18	B	112	0	Exposure too weak		

* Tunnel Not Operating

TABLE 12

NUMERICAL DATA -- MACH 2.0, LOW PRESSURE
Film Identification 6 - 29

Sequential Exposures on Film Strip	Filter	Capacity in MF for Operating Flash Bulb	Resolvable Index of Target	Remarks	Corresponding Line/mm for Unity Magnification	Actual Lines/mm
*1	None	28	6.1	Very good	64.0	426
*2	None	28	5.6	Very good (6.1)	57.0	380
*3	None	28	5.6	Very good	57.0	380
4	None	28	5.6	Very good	57.0	380
5	None	28	5.6	Overexposed	57.0	380
6	None	28	5.6	Good	57.0	380
7	None	56	5.5	Very good, vertical 5.6 better than horizontal	50.8	338
8	None	56	5.5	Very good - like 7	50.8	338
9	None	56	5.5	Very good - like 7	50.8	338
10	N	84	5.3	Faint	40.3	268
11	N	84	5.3	Faint	40.3	268
12	N	84	5.3	Faint	40.3	268
13	N	112	5.3	Very faint	40.3	268
14	N	112	5.3	Very faint, bubbles	40.3	268
15	N	112	5.4	Faint	45.3	302
16	Y	112	5.5	Excellent, vertical better than horizontal	50.8	338
17	G	112	5.5	Good	50.8	338
18	B	112	0	Exposure too weak		

* Tunnel Not Operating

TABLE 13

NUMERICAL DATA -- MACH 2.0, LOW PRESSURE
Film Identification 1 - 30

Sequential Exposures on Film Strip	Filter	Capacity in MF for Operating Flash Bulb	Resolvable Index of Target	Remarks	Corresponding Line/mm for Unity Magnification	Actual Lines/mm
*1	None	28	5.6	Overexposed, vertical better than horizontal	57.0	380
*2	None	28	6.1	Excellent	64.0	426
*3	None	28	5.6	Excellent	57.0	380
4	None	28	5.5	Excellent	50.8	338
5	None	28	6.1	Excellent	64.0	426
6	None	28	5.4	Excellent	45.3	302
7	None	56	5.5	Excellent, vertical 5.6 better than horizontal	50.8	338
8	None	56	5.3	Overexposed (5.5)	40.3	268
9	None	56	5.4	Overexposed	45.3	302
10	N	84	5.3	Faint	40.3	268
11	N	84	5.4	Faint	45.3	302
12	N	84	5.3	Very faint	40.3	268
13	N	112	0	Exposure too weak		
14	N	112	5.4	Good	45.3	302
15	N	112	5.3	Good	40.3	268
16	Y	112	5.5	Overexposed	50.8	338
17	G	112	5.5	Good	50.8	338
18	B	112	0	Exposure too weak		
**19	N		5.5	Very good	50.8	338
**20	N	112	5.5	Very good	50.8	338

* Tunnel Not Operating
** Flash Turned About 90 Degrees

TABLE 14

NUMERICAL DATA -- MACH 2.0, HIGH PRESSURE
Film Identification 2 - 30

Sequential Exposures on Film Strip	Filter	Capacity in MF for Operating Flash Bulb	Resolvable Index of Target	Remarks	Corresponding Line/mm for Unity Magnification	Actual Lines/mm
*1	None	28	5.5	Good	50.8	338
*2	None	28	5.6	Good, vertical 6.1	57.0	380
*3	None	28	5.6	Good	57.0	380
4	None	28	5.5	Very good, horizontal 5.6	50.8	338
5	None	28	5.6	Very good	57.0	380
6	None	28	5.4	Many bubbles	45.3	302
7	None	56	5.6	Excellent, vertical 5.6, horizontal 5.5	57.0	380
8	None	56	5.5	Excellent	50.8	338
9	None	56		Overexposed, blurred		
10	N	84	5.4	Faint	45.3	302
11	N	84	5.4	Faint	45.3	302
12	N	84	5.4	Faint	45.3	302
13	N	112	5.4	Faint	45.3	302
14	N	112	5.4	Faint	45.3	302
15	N	112	5.4	Faint	45.3	302
16	Y	112	5.4	Overexposed	45.3	302
17	G	112	5.4	Good	45.3	302
18	B	112	5.4	Faint	45.3	302

* Tunnel Not Operating

TABLE 15

NUMERICAL DATA -- MACH 2.0, HIGH PRESSURE, INCANDESCENT LIGHT 150 WATT
Film Identification 3 - 30

Sequential Exposures on Film Strip	Filter	Exposure	Resolvable Index of Target	Remarks	Corresponding Line/mm for Unity Magnification	Actual Lines/mm
1	None	4 sec	5.3	Excellent	40.3	268
2	None	4 sec	5.4	Excellent	45.3	302
3	None	4 sec	5.3	Excellent	40.3	268
4	None	4 sec	5.3	Excellent	40.3	268
5	None	4 sec	5.2	Excellent	36.0	240
				(The contrast was generally much lower than with the flash bulb)		

TABLE 16

NUMERICAL DATA -- MACH 2.0, HIGH PRESSURE; INFLUENCE OF VARIATION OF COLLIMATOR FOCAL LENGTH
Film Identification 4 - 30

Sequential Exposures on Film Strip	Deviation of Focal Length	Resolvable Index of Target	Remarks	Corresponding Line/mm for Unity Magnification	Actual Lines/mm
*1	0mm	5.4	Good	45.3	302
*2	0mm	5.4	Good	45.3	302
*3	0mm	5.4	Good	45.3	302
*4	-1mm	5.4	Good	45.3	302
*5	-1mm	5.3	Good	40.3	268
*6	-1mm	5.4	Good	45.3	302
7	-1mm	5.3(5.4)	Faint, disturbed	40.3/45.3	268/302
8	-1mm	Vert 4.5, Horiz 5.2	Good	25.4/36.0	169/240
9	-1mm	5.3(5.4)	Good	40.3/45.3	268/302
10	-2mm	5.3	Faint	40.3	268
11	-2mm	Vert 5.4, Horiz 5.5	Good	45.3/50.8	302/338
12	-2mm	5.3	Faint	40.3	268
13	+1mm	5.3	Good	40.3	268
14	+1mm	5.3	Good	40.3	268
15	+1mm	5.3	Good	40.3	268
16	+2mm	5.3	Good	40.3	268
17	+2mm	Vert 5.2, Horiz 4.6	Good	36.0/28.5	240/190
18	+2mm	5.2	Good	36.0	240

* Tunnel Not Operating
For all pictures: None 28

APPENDIX B

DESCRIPTION OF SUPERSONIC WIND TUNNEL

DESCRIPTION OF SUPERSONIC WIND TUNNEL

The Wright Air Development Center 6-inch x 6-inch Supersonic Wind Tunnel is a closed circuit, continuous-operation type tunnel utilizing fixed nozzle blocks to obtain Mach numbers in the range from 1.50 to 2.50 at 0.25 increments. A set of parallel wall nozzle blocks is also available for obtaining Mach numbers from 0 to choking.

Tests may be conducted at stagnation pressures ranging from 500 to 4,000 pounds per square foot absolute throughout a great portion of the Mach number range, producing a maximum Reynolds number range of approximately 0.2 to 8.6 x 10^6 per foot.

The tunnel is powered by a 1000-horsepower variable speed motor which drives the 12-stage axial flow compressor at controlled rotational speeds from 1800 to 14,400 revolutions per minute. A maximum compression ratio of 4.4 to 1 may be obtained by the use of this compressor. Effeciency at normal operating conditions averages about 70%.

Tunnel stagnation temperature is automatically controlled by a calcium chloride brine system to within ±1°F of a preset value. A stabilization period of 5 to 15 minutes is required after start-up for complete temperature stabilization.

At the present time stagnation pressure is controlled by a manual system, consisting of vacuum and pressure sources, and valves and connecting plumbing. The wind tunnel operator merely adjusts electrically operated valves until the desired pressure is obtained. A sufficiently stable stagnation pressure may be obtained during a normal run by the time the stagnation temperature is stabilized.

The tunnel's air-drying system consists of a pair of activated alumina dryer beds which are used alternately. Water and freon pre-coolers are used to reduce the temperture of the air entering the dryer to +35°F. Air leaving the dryer normally has a dew point in the order of -75°F. The dew point of air within the tunnel is easily maintained at -25°F, or lower, with this system.

Accessory equipment is cooled by a water cooling system serving both a 2-ft x 2-ft supersonic wind tunnel and the 6-inch x 6-inch supersonic wind tunnel.

Pressure measurements are normally made on a 100-tube mercury multi-manometer. Precision manometers and pressure capsules may be used for special tests.

Force measurements are obtained by the use of strain gage balance systems in conjunction with Brown millivolt recorders. All pressure and force measurements are read and recorded manually.

Data reduction is accomplished by the Computing Unit of the Wind Tunnel Branch.

Available optical test facilities consist of a Schlieren system and a Mach-Zehnder interferometer which are built into a single framework. When the instrument is operated primarily as an interferometer a quick change-over is feasible and Schlieren pictures may be inter-spaced as desired. The field-of-view is an ellipse approximately 6 inches x 9 inches in size. The entire test region may be viewed by this instrument.

A normal testing crew consists of the project engineer, tunnel operator, and one mechanic.

Reconnaissance Laboratory, Aeronautical Systems Division, W-P Air Force Base, Ohio. THE INFLUENCE OF SUPERSONIC AIRFLOW ON AERIAL PHOTOGRAPHY, by Hermann R. Mestwerdt and Werner Rambauske. June 1961. 37p. incl. illus. & tables (Proj. 6220; Task 62794) (ASD TN-61-35) Unclassified Report.

Influence of turbulent boundary layer on refraction, dispersion, and light ray scattering investigated as a phenomenon that degrades photographic resolution. Photographs of resolution target made through supersonic wind tunnel with high resolution camera, flash or incandescent illumination, and when wind tunnel operated and did not operate achieved average resolution of 380 1/mm when

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tunnel was not running and average of 302 1/mm when tunnel operated with speeds of Mach 1.5, 2.0, and 2.5 and pressures corresponded to those at 30,000 and 50,000 ft altitude. Loss in resolution of approximately 80 1/mm corresponded to stochastic influence of a 1/3-inch thick boundary layer by light scattering. Conclusion: systems with resolution up to 100 1/mm and usual aperture ratios <u>may</u> not be disturbed greatly by thin turbulent boundary layer.

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Influence of turbulent boundary layer on refraction, dispersion, and light ray scattering investigated as a phenomenon that degrades photographic resolution. Photographs of resolution target made through supersonic wind tunnel with high resolution camera, flash or incandescent illumination, and when wind tunnel operated and did not operate achieved average resolution of 380 1/mm when

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